Analytical Techniques for the Calculation of Leeway as a Basis for Search and Rescue Planning

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Abstract-**Leeway, defined as the movement of the search object through water caused by the action of wind on the exposed surfaces of the object, is fundamental to search planning. Over the past several years, the U.S. Coast Guard (USCG) Research and Development Center (R&DC) and the Canadian Coast Guard (CCG) have participated in leeway studies of various drift targets such as life rafts, evacuation vessels, sailboats, and other targets of interest. The leeway coefficients computed for each drift target generated from these leeway studies will be used in the new USCG Search and Rescue (SAR) planning software, the Search and Rescue Optimal Planning System (SAROPS), to define potential search areas during SAR operations.**

In the fall of 2005, the R&DC conducted leeway testing of two specific drift objects on behalf of the U.S. Naval Submarine Medical Research Laboratory: the Mark-10 Submarine Escape and Immersion Equipment (SEIE) life raft, and the Submarine Emergency Position Indicating Radio Beacon (SEPIRB). These studies were performed off the coast of St. John's, Newfoundland, Canada where open ocean conditions can be obtained within several miles from shore. Multiple drift runs were completed for each type of object to evaluate their behavior in response to various wind and sea conditions, producing object drift data under a wide variety of conditions.

During the course of the study, each target was tracked by an on-board GPS receiver and data logger to yield high-resolution speed and direction over ground data. Wind velocity and sea conditions were measured by meteorological and wave rider buoys deployed within the study area to characterize environmental forcing conditions. The leeway of one SEIE raft was measured directly by a 1200 kHz acoustic Doppler current profiler (ADCP) gimbal-mounted and in a down-looking orientation, as well as multiple Self Locating Datum Marker Buoys (SLDMBs) that reported their respective positions via satellite at 30-minute intervals. Leeway of the remaining objects was determined indirectly by subtracting the surface current vector of adjacent SLDMBs from the drift object vector motion recorded by its onboard GPS receiver. Because all search objects were in the vicinity of the SLDMB field, a comparison between the direct and indirect leeway motion could be made for the ADCP-equipped SEIE raft. This value was then correlated to recorded wind speed and direction, and subjected to error analysis and statistical validation.

This paper focuses on the methodology employed during the field study and provides a detailed description of the post-processing routines used to derive leeway coefficients for the SEIE for U.S. Navy search planning, and for use by the USCG in its SAROPS planning software. Estimates of the surface current for each drift target to support indirect leeway calculations relied on a statistical interpolation technique and consisted of steps described in the paper below. The resulting time series constituted a data base for the calculation of downwind and crosswind leeway coefficients, derived from a least-squares linear regression between the corresponding velocity components of wind and target drift. The success of the indirect approach is evaluated by comparing the estimates with directly measured velocities. It was concluded that this statistical interpolation technique performed particularly well when the drifting target stayed within an imaginary polygon delineated by the available SLDMBs.

Three of the four rafts considered in the study drifted with 12-15° leeway angles to the right of the wind direction. Downwind leeway coefficient was 0.02 for the drogued rafts and 0.03 for the undrogued rafts. Scatter of estimated leeway velocity with respect to wind speed suggested a tighter relationship for higher wind speeds (>7 m/sec).

I. Introduction

The U.S. Coast Guard (USCG) Research and Development Center (R&DC) and the Canadian Coast Guard (CCG) have participated in joint leeway studies in the waters off St. John's, Newfoundland, since the early 1990s. These field measurement programs have provided much of the empirical data now used in Search and Rescue (SAR) planning by both agencies. This partnership has also permitted the application of consistent data collection and analysis methods and development of drift coefficients for a wide array of common SAR objects, all of which now serve as the basis for algorithms utilized in the USCG's Search and Rescue Optimal Planning System (SAROPS) software.

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The U.S. National SAR Supplement defines leeway as "the movement of the search object through water caused by the action of wind on the exposed surfaces of the object" [1]. To standardize leeway field measurements, Reference [2] refined leeway as the velocity vector relative to the downwind direction at the search object as it moves relative to the surface current, as measured between 0.3 m and 1.0 m depth, caused by the winds (adjusted to a reference height of 10 m) and waves. Thus, estimation of leeway velocities requires data pertaining to the speed and direction of a particular SAR object, as well as information regarding wind velocity and sea surface current velocity for the approximate location of the object during the period of exposure. Based on these parameters the leeway calculation consists of two principal steps:

1) subtract the velocity of sea surface current from the velocity of a target to derive the velocity of target propagation relative to moving sea surface; and

2) subtract the wind direction from direction of target propagation relative to sea surface.

The ultimate practical goal of the analysis is to define the least-squares parameters of the assumed linear relationship between wind speed and downwind and crosswind components of the leeway velocity.

Science Applications International Corporation (SAIC) supported the USCG Research and Development Center (R&DC) in a comprehensive leeway study conducted off the coast of St. John's, Newfoundland, in October and November 2005. The fall 2005 study was performed to determine the leeway coefficients associated with several types of drift objects including the Mark-10 Submarine Escape and Immersion (SEIE), single-man life rafts issued to U.S. Navy submariners. This element of the leeway study was funded by the Naval Submarine Medical Research Laboratory (NSMRL) with the ultimate goal of accelerating the identification and rescue of survivors in naval SAR environments by reducing the amount of time required to find survivors at sea; specifically, escapees from a sunken submarine who are utilizing the SEIE life raft. Each standard SEIE raft is equipped with a drogue, or sea-anchor, that provides sufficient drag to properly orient a drifting raft in a manner that would minimize the exposure of the occupant to the wind and sea.

A number of instrumented drift targets (i.e., SEIE rafts) were constructed as part of the 2005 leeway study, then deployed in open water and tracked as they drifted off the coast of St. John's, Newfoundland, under carefully observed environmental conditions. The drift targets were equipped with on-board GPS data-logging equipment to accurately track their movement over time. In addition, ARGOS platform transmitter terminals (PTTs) were also included with the instrument packages to periodically transmit positional data information that could be accessed in near real-time to aid in target tracking and facilitate recovery. Some of the deployed rafts were equipped with a gimbal-mounted 1200 kHz Teledyne RD Instruments Acoustic Doppler Current Profiler (ADCP) to provide a direct measure of near-surface currents and determine the raft motion relative to the water. In other cases, an indirect estimate of the near-surface field in vicinity of the drift targets was provided by an array of MetOcean Data Systems Limited's self-locating datum marker buoys (SLDMBs) released during each deployment. Detailed meteorological data (i.e., wind direction and speed, air and water surface temperature), along with Eulerian measurements of near-surface current speed and direction, were provided by an Aanderaa Data Instruments' Coastal Monitoring Buoy (CMB) that was deployed in the approximate center of the primary operations area. This array of instrumentation provided all of the necessary data to evaluate the relationship between the wind velocity and the leeway drift for each type of SAR object tested.

A total of five individual drift runs of various durations were conducted under different sea states and meteorological conditions, with the SEIE rafts deployed in both drogued and undrogued configurations. A typical drift run would begin with the deployment of multiple rafts plus other types of drift targets in a tight cluster within the primary operations area. These drift targets would then be bounded by a series of four or more SLDMBs released at a nominal distance of 1 km for Drift 1 and 5 km for Drifts 2 through 5 in each cardinal direction (i.e., 000, 090, 180, and 270 degrees True) around the central drift target deployment location. This deployment scheme provided a boundary polygon that would conceptually move with the drift targets and provide Lagrangean measurements of the surface currents acting upon the drift targets.

I. PRELIMINARY DATA ANALYSIS

Target position and propagation velocity

The first element of the analyses entailed detailed visual inspection of the drift target and SLDMB trajectories for each of the five drift runs, and removing any obvious outliers in trajectories. The time series of eastward and northward velocity components were then computed by differencing successive GPS positions for each drift target and the associated SLDMB data to highlight small-scale position errors relative to the large and obvious position shifts detected during the initial inspection of the position data. Although small in terms of position data, these shifts were statistical outliers of the resulting velocity time series. To automate detection and editing of the outliers, each velocity time-series data set used in this study

was passed through an order statistics filter followed by a Chebyshev filter to split each time- series into high- and low-frequency portions. The standard deviation of each time series was then estimated for the high-frequency portion of the data. If at a given instant the magnitude of the high-frequency velocity exceeded three standard deviations, the high-frequency value was identified as an outlier and replaced by a linear interpolation. The corresponding total velocity value was obtained by adding the interpolated high-frequency value to the low-frequency component at the corresponding time instant. The cycle was then repeated until no outliers remained in the time series. The processed time series, those of both position and velocity, were further smoothed to facilitate subsequent decimation to either the 10-minute or 30-minute time grids used in further analysis. The 10-minute time grid was used for all data involved in analysis based on ADCP measurements of current velocity (the direct case of leeway analysis), while the 30-minute time grid was used in analyses based on inferred rather than measured current velocity (the indirect case).

Wind velocity data

The necessary meteorological data (i.e., wind direction/speed, air/water surface temperature) were measured via sensors installed at the deployed CMB mooring. These data were collected with the 5-minute sampling interval and provided observations for the entire period of the field work, with the exception of the last few hours of the first drift run (Fig 1). As was the case with all types of data involved in the analysis, the time series of meteorological parameters were first run through a procedure for detection and replacement of statistical outliers. These data were then smoothed and decimated to form time series sampled with either the 10-minute or 30-minute time-step used in further analysis. The recorded wind magnitude was adjusted from the 2.6-m sensor height to the 10-m reference height (as required by the leeway speed definition) following the algorithm by Ref [3]. The algorithm is implemented in The Math Works, Inc.'s MATLAB® <cdntc.m> routine included in the Air-Sea toolbox (http://woodshole.er.usgs.gov/operations/sea-mat/).

Sea surface current

Current velocity in a sea surface layer at each position of a drifting target was either directly measured by an on-board ADCP (direct method) or inferred from the observed motion of SLDMBs that were available at a given time in the area (indirect method).

A. Direct case: ADCP measurements

Obtaining measurements of the current field in the direct case was a straightforward process, as one SEIE raft was deployed with a downward-looking ADCP onboard during Drifts Two and Four. The recovered ADCP data provided direct measurements of the drogued raft velocity relative to the near-surface waters, which was exactly the velocity required by the definition of the leeway motion. In this case, data processing was reduced to selecting data for the appropriate depth, detecting and replacing outliers, and smoothing and decimating data into the 10-minute time step.

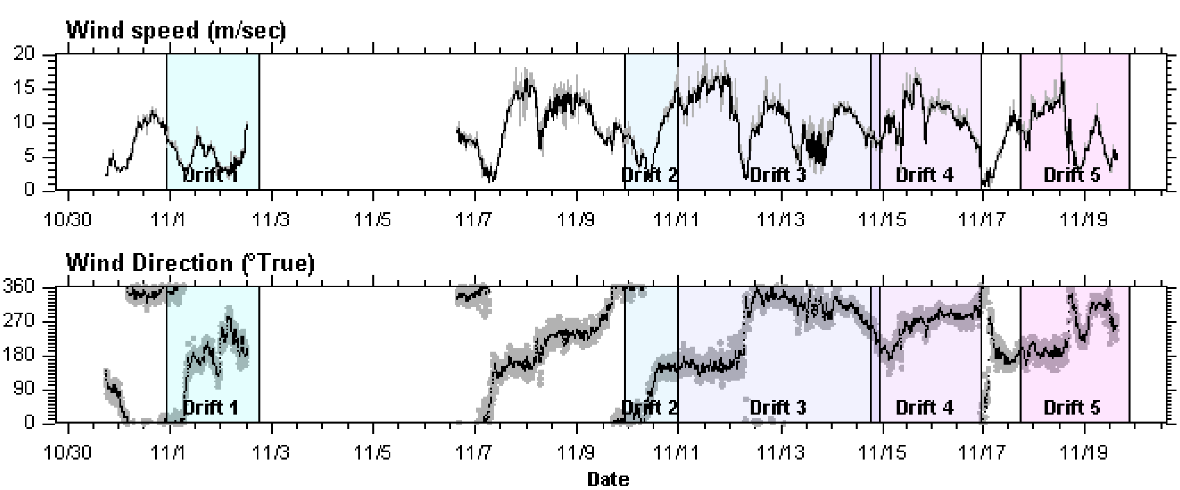

Figure 1. Wind speed (top panel) and direction (bottom panel) measured at the CMB mooring. Shown time series reflect adjustment of the measured wind velocity to the 10-m reference height. Instantaneous values are shown in gray; 1-hour low-passed values – in black. Shaded areas indicate time-frame of drift runs. Drift numbers appear on the bottom of each panel.

The raw, 2-second time-series ADCP data were averaged over a 5-minute interval to remove high-frequency interferences caused by waves, raft motion, and surface noise. The data were acquired within 25-cm depth bins, and the initial averaging maintained data within these same bins. Due to acoustic blanking around the transducer and the depth of the instrument below the water surface, the first useable data bin began at a depth of approximately 75 cm. By convention, ADCP current measurements are associated with the vertical center of each data bin so that, in this case, the data relevant for the study were related to the first useable bin, which was centered at a depth of approximately 87.5 cm. The obtained ADCP data were compared with velocities calculated from the trajectories of the SLDMBs deployed in the area during the same time period to confirm consistency between the data sets.

B. Indirect case: inferred velocity field

The indirect method was computationally more involved, but it was a requirement to obtain an optimized estimate of current velocity at a target position for each considered time instant. The data available for the estimation consisted of current velocities derived from the trajectories of SLDMBs located in the area at the time instant through the application of a variant of the Statistical Interpolation (SI) technique, also known as the Objective Analysis procedure [4] [5]. The velocity field at each time instant was considered to consist of a spatial mean component and a residual velocity. Spatial mean for the time instant was assumed to be the same for all positions in the area and equal to the arithmetic average of SLDMB velocities for a given time. The residual velocity was comprised of the difference between the total velocity of an SLDMB and the spatial mean.

In accordance with the SI, the estimate of the residual velocity of a current at a given target position was qualitatively similar to a weighted average of the residual velocities of the SLDMBs involved into calculation. The weighting factor depended on spatial correlation of the velocity field. This spatial correlation was assumed to be isotropic, as it did not depend on direction and was a function of only a distance between two locations. Also, the underlying process was assumed to be stationary, so that the correlation function did not change with time. The weight for a particular SLDMB within the calculation was defined by the velocity correlation attributable to the distance between the SLDMB and the target as well as by the correlations between all possible pairs of the SLDMBs taken into account in a calculation for the given time step. In addition to providing a velocity estimate at the drift target, the SI also produced an estimate of the component of spatial variance that was not recovered by the calculation; this is referred to as the error variance. The magnitude of the error variance relative to the total variance of the field provided an indication of the statistical quality of the estimated current velocities.

The spatial correlation function necessary for the calculation of the surface current field was estimated from the available data. For this purpose, the information obtained by SLDMBs from all five drift runs was assembled into one data set. The data were then grouped into 1-km bins in accordance with the separation distance between two SLDMBs at the same time step. The correlation value was then calculated between residual velocities within each spatial bin. Finally, an algebraically defined curve (an exponentially modulated cosine) was fitted to the correlation values calculated for all distance bins. This fitted curve constituted the spatial correlation function used in the SI estimation.

The total velocity field was split into three different components corresponding to different time scales to further refine the SI estimation. The SI procedure was applied separately to each component such that the different components were separated by high-, band- and low-passed filtering of the velocity time series. These components included variations with periods less than 10 hours, 10 to 24 hours and longer than 24 hours, respectively. From a physical point of view, each extracted component of the total velocity field represented currents of different nature. Notably, the band-pass component included tidal and inertial currents. From the SI perspective, the most important feature of performing the procedure separately for different portions of the total field is the fact that different physical processes are characterized not only by different time scales, but also by different spatial scales; and therefore, by different spatial means and correlation functions, the fundamentals of the SI computations.

Results of the SI velocity estimations for Drifts 2 and 4 were compared with the direct current measurements derived from the ADCP equipped SEIE raft data. This comparison indicated SI performance greatly depends on spatial configuration of data points (SLDMBs) available at a given time. For instance, the SI estimated velocities compared better with the measured velocities from Drift 2 (Fig 2) than those from Drift 4 (Fig 3). This finding was primarily due to the fact that the ADCP-equipped raft remained within boundary polygon formed by the four SLDMBs deployed as part of Drift 2. Also, the distance between the SEIE raft and the SLDMBs, as well as the distances between the SLDMBs, remained within the radius of

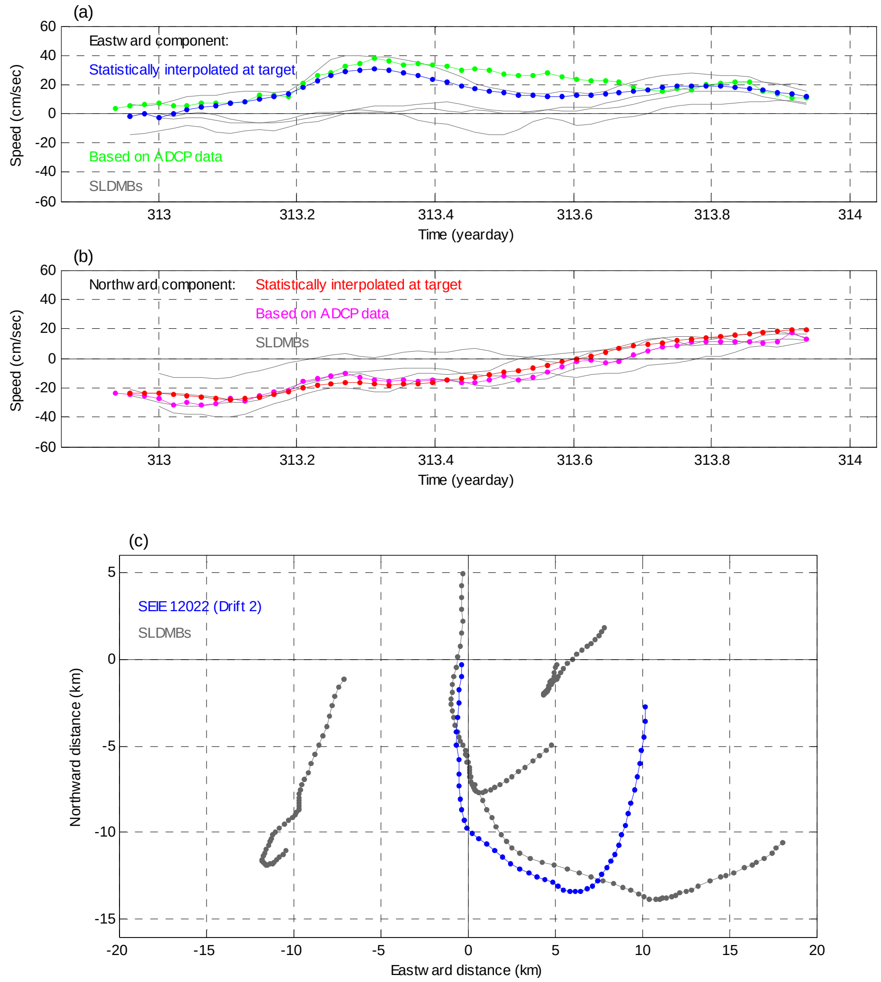

Figure 2. Panels (a) and (b) show the time-series of the statistically interpolated and ADCP-measured components of near-surface current field at the drogued raft (SEIE 12022) during Drift Two. Panel (c) shows a plan view of the raft and SLDMB tracks over the course of the drift. The CMB is located at the origin of the axes.

substantial velocity correlations during Drift 2. Thus, the SLDMBs sampled different sections of the area traversed by the drifting raft and the current velocity data provided by all the SLDMBs contributed to the surface current velocity estimate at the raft position. This was not the case with Drift 4 as the SEIE raft quickly drifted outside the SLDMB boundary polygon, resulting in data that were much less valuable for estimation of current velocity at the raft location.

II. LEEWAY CALCULATIONS.

The final element of the analyses was the development of the downwind and crosswind leeway coefficients for each of the drift targets. Separate data files were developed for each of the drift targets during the course of the data processing effort. The primary elements of these data files were:

1) the filtered GPS time and position data for a drift target;
2) the computed velocity components of the drift target;
3) the relevant data about wind speed and direction from the CMB; and
4) the current velocity field that was developed for the drift target.

As mentioned above, each time series based on direct current measurements were spaced at 10-minute intervals, while those derived from indirect current measurements were spaced at 30-minute intervals. In the direct case, the ADCP velocity data

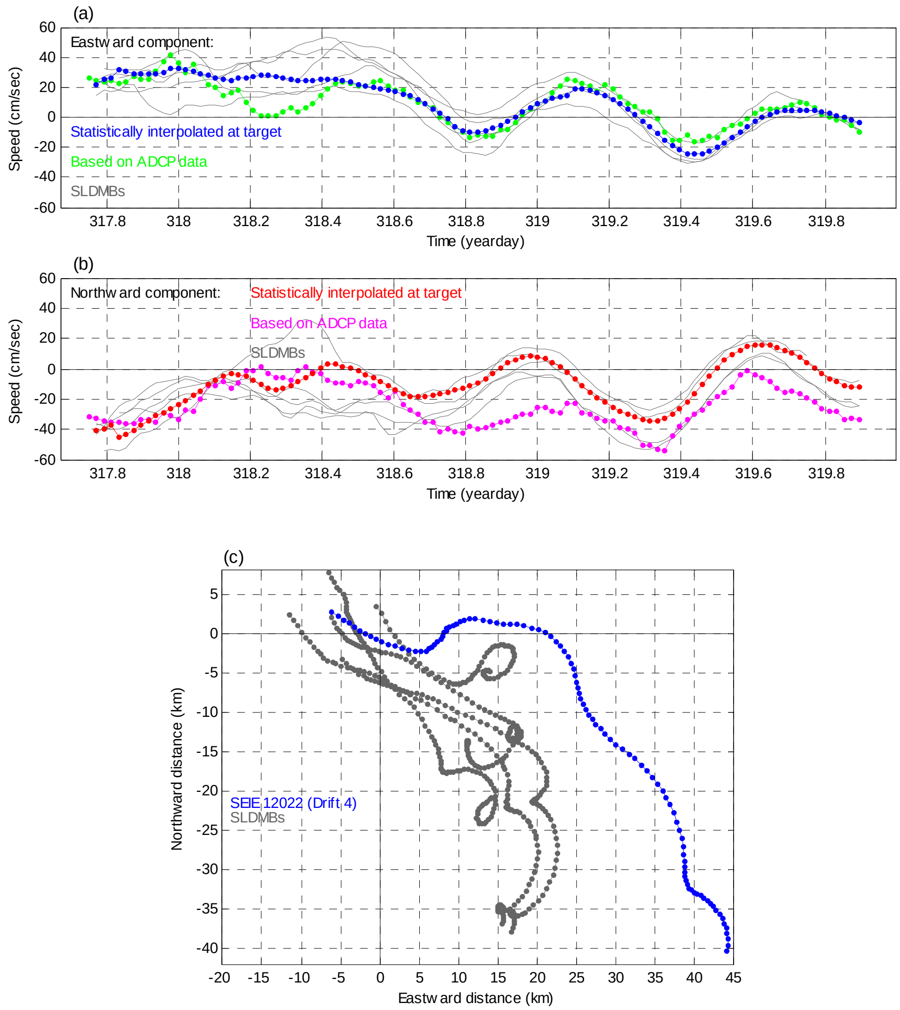

Figure 3. Panels (a) and (b) show the time-series of the statistically interpolated and ADCP-measured components of near-surface current field at the drogued raft (SEIE 12022) during Drift 4. Panel (c) shows a plan view of the raft and SLDMB tracks over the course of the drift. The CMB is located at the origin of the axes.

provided a direct measure of the motion of the target relative to the motion of sea surface layer, as required by the leeway definition. In the indirect case, the SI estimated velocity provided a measure of the sea surface motion relative to ground. So, in order to comply with the leeway definition, velocity of the target relative to sea surface was obtained by subtracting the target motion relative to ground (derived from GPS measurements) from the SI estimated surface current velocity. The leeway velocity components themselves were computed by subtracting the wind direction from the direction of the target motion relative to the sea surface. Progressive vector diagrams were then generated to visualize the movement of the target relative to the downwind direction for the entire duration of the drift

The leeway velocity components were then used to estimate parameters of the relationship between the wind speed and the downwind and crosswind leeway motion for each target from each drift. Past studies have modeled the relationship between wind speed and leeway motion as linear [2]. The linear regression model is of the form:

$$V_L = Y + slope * V_{10}$$

where:

V_L is the leeway speed;
Y is the y-intercept;
slope is the slope of the regression line; and
V_{10} is the wind speed at 10 m above the sea surface.

To facilitate both conceptual and computational simplicity, the model was accepted as the standard for a first order prediction of the leeway motion in real SAR operations. Also, both unconstrained (Y is a free parameter) and constrained (Y = 0) linear models were employed. This study was to follow the established standard, estimating parameters for both constrained and unconstrained linear regressions for the downwind and crosswind leeway speeds relative to the wind speed at a 10 m reference height above the sea surface. In addition to the leeway velocity, the leeway angle for each drift target was analyzed as well.

III. RESULTS

Due to the differences in the quality of the obtained current field estimates, each drift target was first analyzed individually. After the individual leeway parameters were computed, the data were then grouped by drift target type (i.e., drogued-SEIE raft, undrogued-SEIE raft, etc.), so that the average results could be computed and the consistency of those results evaluated.

Figs 4, 5, 6 and 7 display the progressive vector diagrams, the leeway angle, down- and cross-wind leeway velocity components for the drogued ADCP-equipped SEIEs and undrogued SEIEs associated with several drift runs. Three of the four rafts under discussion drifted somewhat to the right of the wind direction. The efficiency of wind speed conversion into the downwind leeway motion (measured by the "*slope*") is on the order of 2% for the drogued SEIE rafts and on the order of 3% for the undrogued rafts. Qualitatively, the difference appears to be reasonable, since the drogued rafts were heavier and have supplemental drag relative to the undrogued SEIE rafts due to both the onboard ADCP equipment and the sea-anchor device. The crosswind leeway component does not seem to reveal any statistically significant dependence on wind speed. In general, tighter scatter of the leeway angle and of the downwind leeway component suggest a tighter relationship for elevated wind speeds (>7 m/sec).

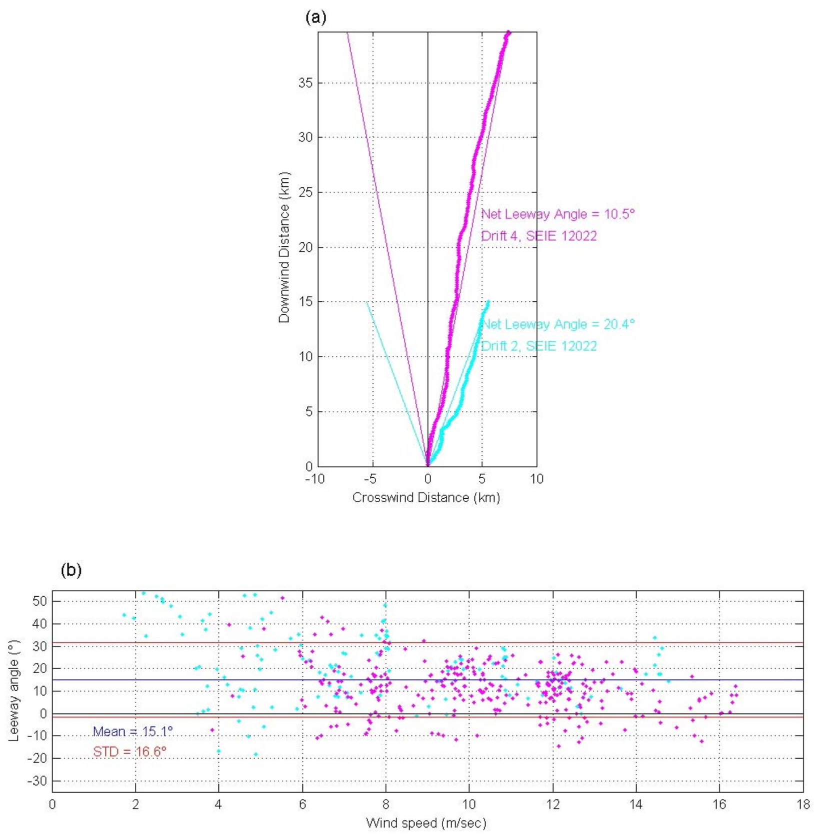

Figure 4. Panel (a) shows progressive vector diagrams for the drogued rafts from Drifts 2 and 4. Panel (b) is a scatter plot of the computed leeway angle relative to the observed wind speed, as well as the computed mean and standard deviation of the leeway angle. The leeway angle was significantly more variable at wind speeds below approximately 7 m/s.

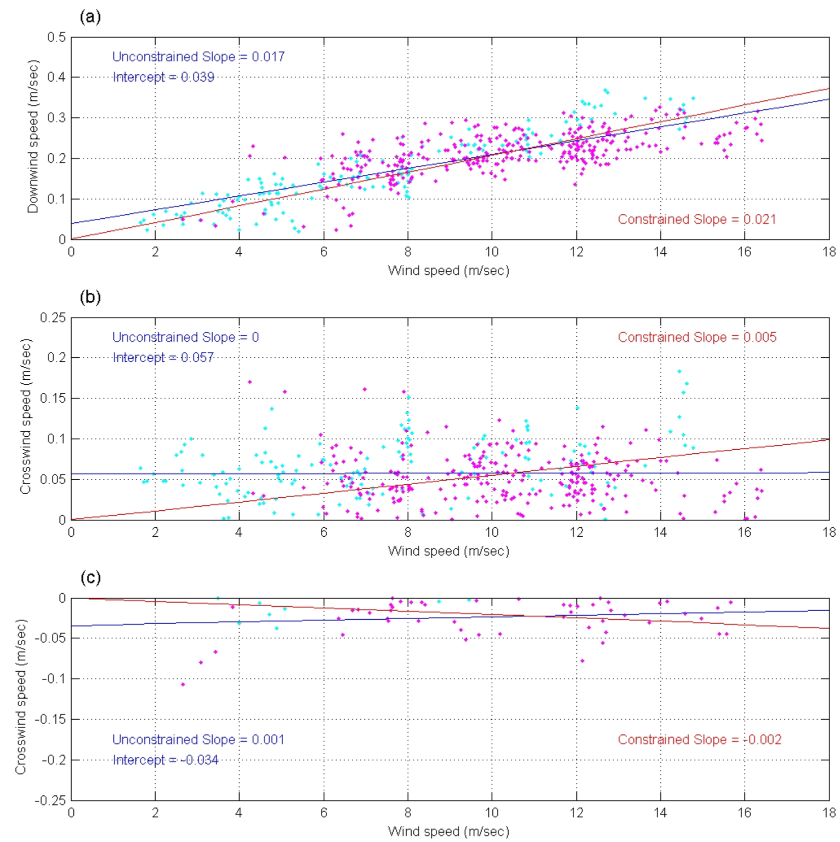

Figure 5. The constrained and unconstrained downwind and crosswind (positive and negative) leeway components computed for the drogued rafts from Drifts 2 and 4.

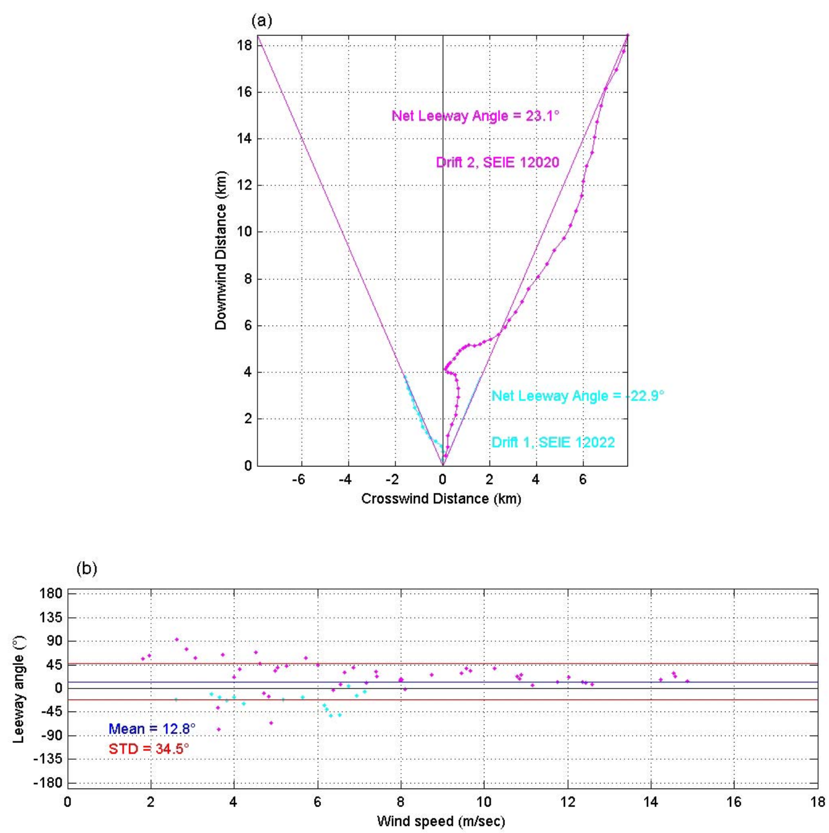

Figure 6. Panel (a) shows the progressive vector diagrams for the undrogued rafts from Drifts 1 and 2. Panel (b) is the scatter plot of the computed leeway angle relative to the observed wind speed, as well as the computed mean and standard deviation of the leeway angle measurement. Because the raft from Drift 1 was partially submerged and flooded on recovery, only the valid data for the first eight hours of this drift have been included in the leeway computations.

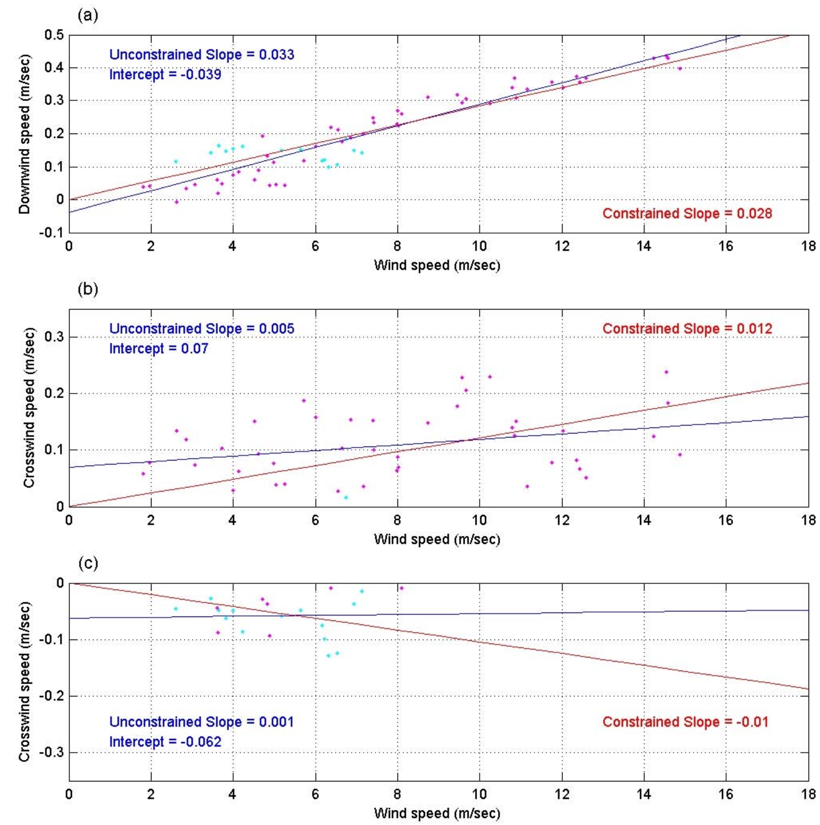

Figure 7. The constrained and unconstrained downwind and crosswind (positive and negative) leeway components computed for the undrogued rafts from Drifts 1 and 2.

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